Structure Functions & low-x group: low-x summary

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- Overview of the group presentations
- Summary of the low-x presentations
- Conclusions

Overview of group presentations

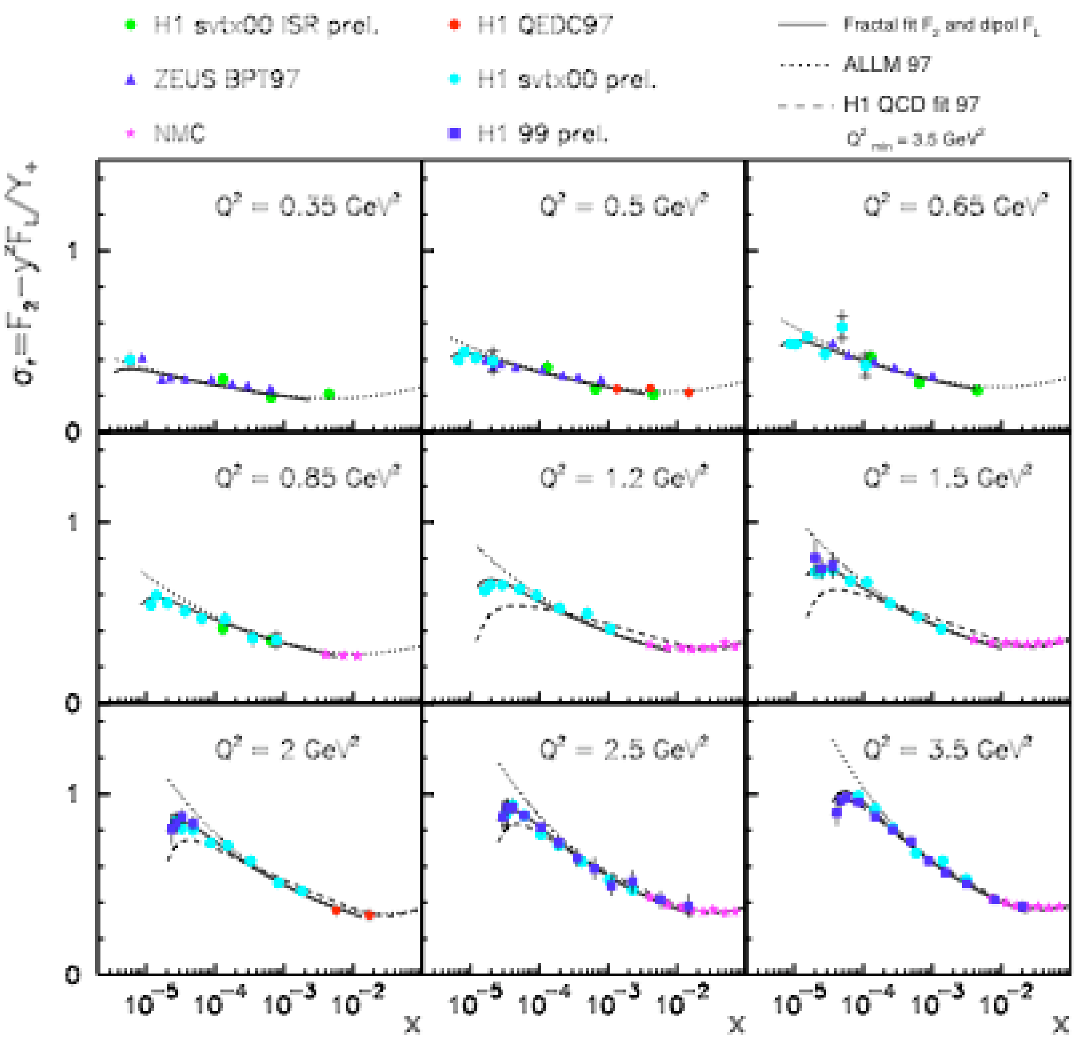
- **Structure function measurements at low x**
  - F_2 & F_L measurements at low Q^2 (H1)
  - Averaging of HERA F_2 data
- Structure function measurements at high x
- Structure functions (theory)
  - NNLO analysis of unpolarised DIS structure functions
  - Testing NLO BFKL resummation
- **Low-x physics at RHIC**
- **Low-x & saturation (theory)**
- High-x theory
  - Factorisation & event generators
- Joint session with EWK group
- **Global PDF analyses**
- Future of PDFs
  - Impact of HERA-II data on the proton PDFs

Structure Functions at low x

- F_2 measurements using QED Comptons (H1/Lobodzinska)
- Measurements of F_2 & F_L at low Q^2 (H1/Petrukhin)
- Averaging of ZEUS & H1 structure function data (Glazov)

F_2 & F_L measurements at low Q^2 (H1)

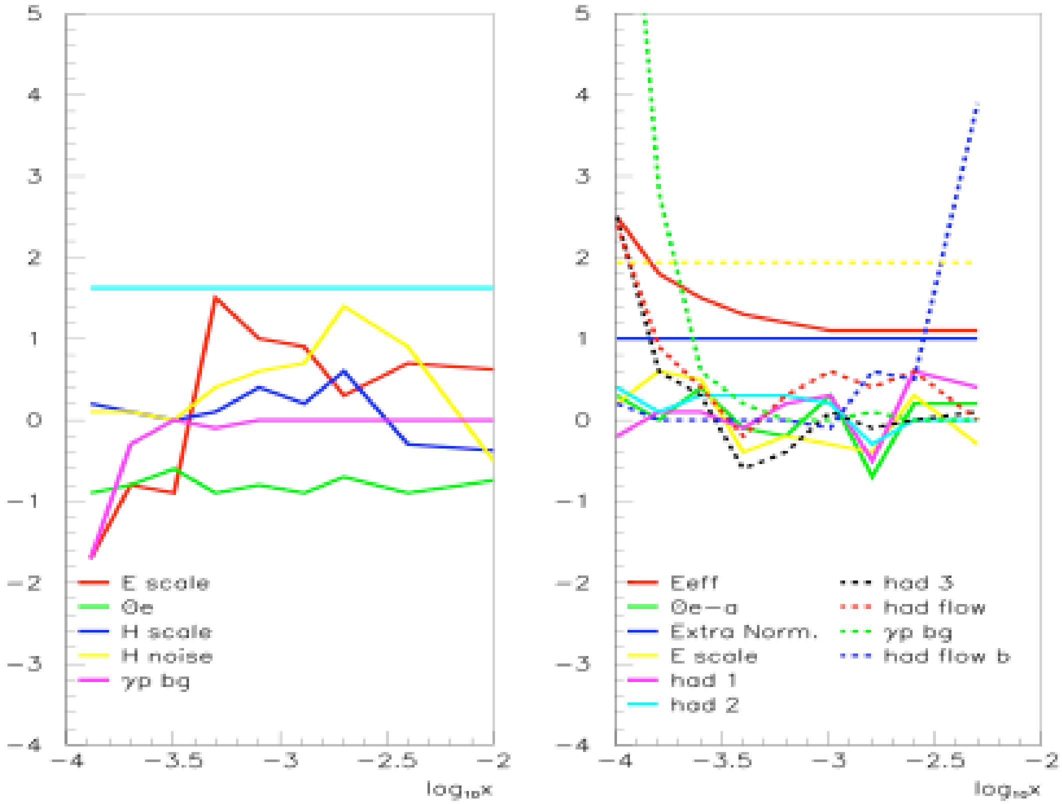
(E. Lobodzinska/A. Petrukhin)



- Precision low Q^2 F_2 measurements
- Number of different methods
- Extension into the higher x region - overlap with fixed target data
- Close to completing HERA-I structure function programme

Averaging of H1 & ZEUS data

(S. Glazov)

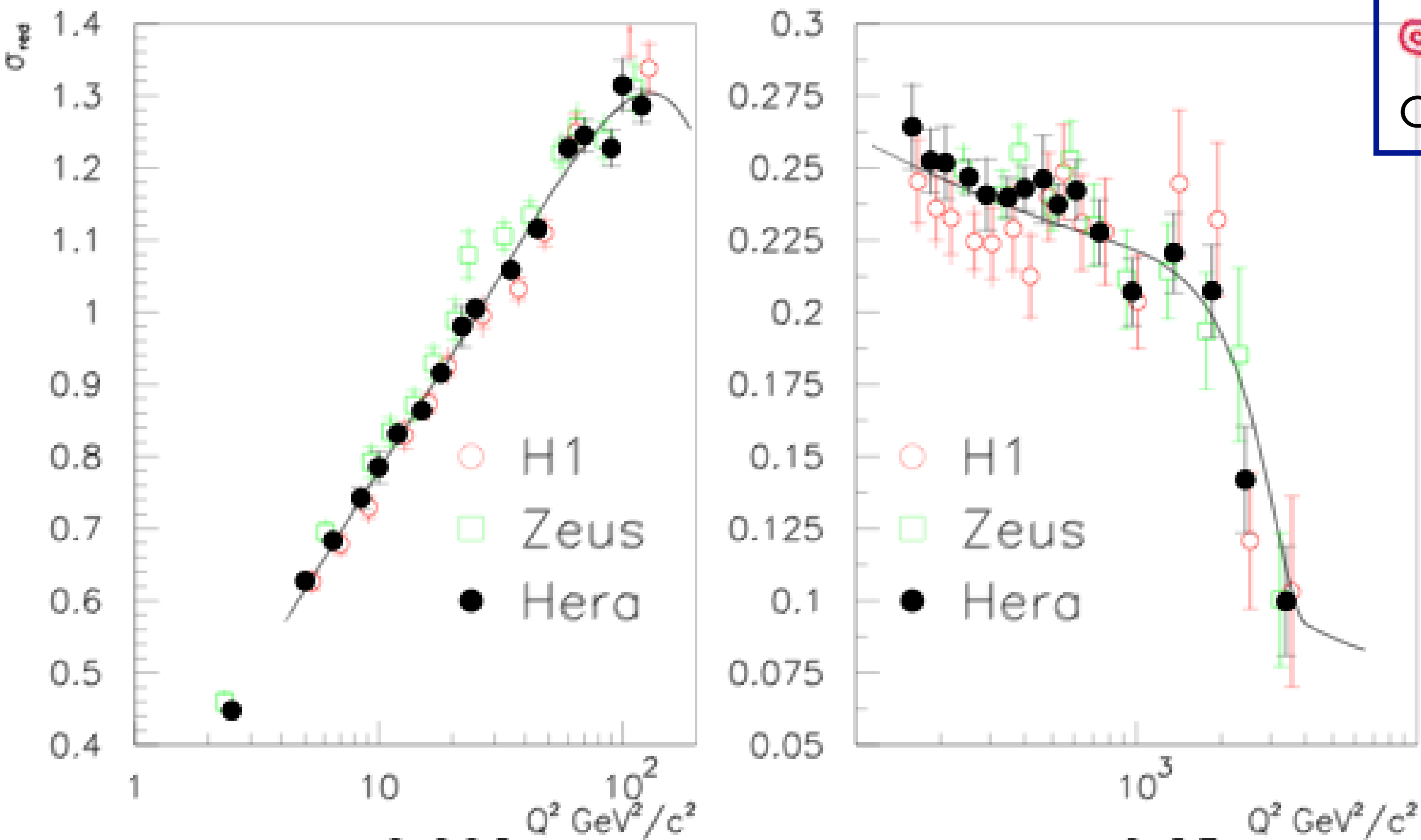


Sensitivity to syst. errors for $Q^2 = 6.5\ \mathrm{GeV}^2$

- Surprising (?) result: reduction of systematic uncertainties after averaging
- Experiments constraining each other …

Averaging of H1 & ZEUS data

(S. Glazov)



x=0.002 **x=0.25**

- Studies continuing

Low x theory

- NNLO scheme invariant evolution of unpolarised DIS structure functions (Guffanti)
- Tests of NLO BFKL resummation (Royon)
- Factorisation & event generators (Zu)

NNLO scheme invariant evolution of unpolarised DIS structure functions

(A. Guffanti)

- Aim:
  - α_S with theoretical uncertainty ~ 1% to match experimental uncertainty
  - PDFs with fully correlated errors
- Use factorisation scheme-invariant evolution
  - Evolution equations with physical anomalous dimensions
- Perform one-dimensional fit to determine α_S
- Initial results on F_2
- Work still ongoing (inclusion of heavy flavours, fit to data, one parameter fit to Λ_{QCD})

NNLO scheme invariant evolution of unpolarised DIS structure functions

F_2, $\partial F_2/\partial t$ - **NNLO**

(A. Guffanti)

Next-to-next-to-Leading Order:

$$K_{22}^{N(2)} = K_{2d}^{N(2)} = 0$$

$$K_{d2}^{N(2)} = \frac{1}{4}\left(\gamma_{qq}^{N(2)}\gamma_{gg}^{N(0)} + \gamma_{qq}^{N(0)}\gamma_{gg}^{N(2)} - \gamma_{qg}^{N(2)}\gamma_{gq}^{N(0)} - \gamma_{qg}^{N(0)}\gamma_{gq}^{N(2)} + \gamma_{qq}^{N(1)}\gamma_{gg}^{N(1)} - \gamma_{qg}^{N(1)}\gamma_{gq}^{N(1)}\right)$$

$$+\frac{\beta_0}{2}\left[C_{2,q}^{N(1)}\left(\gamma_{qq}^{N(1)} + \gamma_{gg}^{N(1)}\right) - \left(C_{2,q}^{N(1)}\right)^2\left(\gamma_{qq}^{N(0)} + \gamma_{gg}^{N(0)}\right) - 3C_{2,q}^{N(1)}\gamma_{qq}^{N(1)}\right]$$

$$-\beta_0\left[\gamma_{qq}^{N(2)} + 2\gamma_{gq}^{N(0)}\left(C_{2,g}^{N(2)} - C_{2,g}^{N(1)}C_{2,q}^{N(1)}\right) - C_{2,q}^{N(2)}\left(\gamma_{qq}^{N(0)} + \gamma \ldots\right.\right.$$

$$+\beta_0^2\left[3\left(C_{2,q}^{N(1)}\right)^2 - 4C_{2,q}^{N(2)}\right] + \frac{\beta_1}{2}\left[\gamma_{qq}^{N(1)} - C_{2,q}^{N(1)}\left(\gamma_{qq}^{N(0)} + \gamma_{gg}^{N(0)} \ldots\right.\right.$$

$$-\frac{\beta_1}{2\beta_0}\left(\gamma_{qq}^{N(1)}\gamma_{gg}^{N(0)} + \gamma_{qq}^{N(0)}\gamma_{gg}^{N(1)} - \gamma_{qg}^{N(1)}\gamma_{gq}^{N(0)} - \gamma_{qg}^{N(0)}\gamma_{gq}^{N(1)}\right)$$

$$+\frac{3}{4}\frac{\beta_1^2}{\beta_0^2}\left(\gamma_{qq}^{N(0)}\gamma_{gg}^{N(0)} - \gamma_{qg}^{N(0)}\gamma_{gq}^{N(0)}\right) - \frac{\beta_2}{2\beta_0}\left(\gamma_{qq}^{N(0)}\gamma_{gg}^{N(0)} - \gamma_{qg}^{N(0)}\gamma \ldots\right.$$

$$+\frac{1}{\gamma_{qg}^{N(0)}}\left\{\frac{\beta_1}{2}\gamma_{qq}^{N(0)}\left[C_{2,g}^{N(1)}\left(\gamma_{qq}^{N(0)} - \gamma_{gg}^{N(0)}\right) - \gamma_{qg}^{N(1)}\right] + 2\beta_0^3 C_{2,q}^{N(1)} \ldots\right.$$

$$+\beta_0^2\left[4\gamma_{qq}^{N(0)}\left(C_{2,g}^{N(2)} - C_{2,g}^{N(1)}C_{2,q}^{N(1)}\right) - C_{2,g}^{N(1)}C_{2,q}^{N(1)}\left(\gamma_{qq}^{N(0)} - \gamma_{gg}^{N(\ldots}\right.\right.$$

$$+C_{2,g}^{N(1)}\gamma_{qq}^{N(1)} + \left(C_{2,g}^{N(1)}\right)^2\gamma_{gq}^{N(0)}\Big]$$

$$+\beta_0\left[C_{2,g}^{N(1)}C_{2,q}^{N(1)}\gamma_{qq}^{N(0)}\left(\gamma_{qq}^{N(0)} - \gamma_{gg}^{N(0)}\right) + \gamma_{qq}^{N(0)}\left(C_{2,g}^{N(1)}\gamma_{gg}^{N(1)} + \ldots\right.\right.$$

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$$+\frac{\beta_0}{2}\left[C_{2,g}^{N(1)}\left(\gamma_{qq}^{N(1)}\gamma_{gg}^{N(0)} + \gamma_{gq}^{N(0)}\gamma_{qg}^{N(1)} - 3\gamma_{qq}^{N(0)}\gamma_{qq}^{N(1)}\right) + \gamma_{qq}^{N(1)}\gamma_{qg}^{N(1)}\right.$$

$$+\left(C_{2,g}^{N(1)}\right)^2\left(\gamma_{gg}^{N(0)}\gamma_{gq}^{N(0)} - 3\gamma_{gq}^{N(0)}\gamma_{qq}^{N(0)}\right)\Big] + \beta_0\gamma_{qg}^{N(2)}\gamma_{qq}^{N(0)} + \beta_1\beta_0 C_{2,g}^{N(1)}\gamma_{qq}^{N(0)} - \beta_0 C_{2,g}^{N(2)}\left(\gamma_{qq}^{N(0)}\right)^2\Big\}$$

$$+\frac{1}{\left(\gamma_{qg}^{N(0)}\right)^2}\left\{-2\beta_0^3\left(C_{2,g}^{N(1)}\right)^2\gamma_{qq}^{N(0)} + 2\beta_0^2\left[\left(C_{2,g}^{N(1)}\right)^2\left(\left(\gamma_{qq}^{N(0)}\right)^2 - \gamma_{qq}^{N(0)}\gamma_{gg}^{N(0)}\right) - C_{2,g}^{N(1)}\gamma_{qq}^{N(0)}\gamma_{qg}^{N(0)}\right]\right.$$

$$+\beta_0\left[\left(C_{2,g}^{N(1)}\right)^2\left(\gamma_{qq}^{N(0)}\right)^2\gamma_{gg}^{N(0)} + C_{2,g}^{N(1)}\left(\gamma_{qq}^{N(0)}\right)^2\gamma_{qg}^{N(1)} - C_{2,g}^{N(1)}\gamma_{qq}^{N(0)}\gamma_{gg}^{N(0)}\gamma_{qg}^{N(1)}\right.$$

$$\left.\left.-\frac{1}{2}\left(\left(C_{2,g}^{N(1)}\right)^2\left(\gamma_{qq}^{N(0)}\right)^3 + \gamma_{qq}^{N(0)}\left(\gamma_{qg}^{N(1)}\right)^2 + \left(C_{2,g}^{N(1)}\right)^2\gamma_{qq}^{N(0)}\left(\gamma_{gg}^{N(0)}\right)^2\right)\right]\right\}$$

$$K_{dd}^{N(2)} = \gamma_{qq}^{N(2)} + \gamma_{gg}^{N(2)} - 4\beta_0\left[\left(C_{2,q}^{N(1)}\right)^2 - 2C_{2,q}^{N(2)}\right] - 4\beta_2 + \left(\frac{\beta_1^2}{\beta_0^2} - \frac{\beta_2}{\beta_0}\right)\left(\gamma_{qq}^{N(0)} + \gamma_{gg}^{N(0)}\right)$$

$$-\frac{\beta_1}{\beta_0}\left(\gamma_{qq}^{N(1)} + \gamma_{gg}^{N(1)} - 2\beta_1\right) + \frac{4\beta_0}{\gamma_{qg}^{N(0)}}\left\{4\beta_0\left(C_{2,g}^{N(2)} - C_{2,q}^{N(1)}C_{2,g}^{N(1)}\right) + \gamma_{qg}^{N(2)}\right.$$

$$\left.+\left(\gamma_{qq}^{N(0)} - \gamma_{gg}^{N(0)}\right)\left(C_{2,g}^{N(1)}C_{2,q}^{N(1)} - C_{2,g}^{N(2)}\right) - C_{2,g}^{N(1)}\left(\gamma_{qq}^{N(1)} - \gamma_{gg}^{N(1)} - 2\beta_1\right) - \left(C_{2,g}^{N(1)}\right)^2\gamma_{gq}^{N(0)}\right\}$$

$$+\frac{2\beta_0}{\left(\gamma_{qg}^{N(0)}\right)^2}\left\{-4\beta_0^2\left(C_{2,g}^{N(1)}\right)^2 - 4\beta_0 C_{2,g}^{N(1)}\left[\gamma_{qg}^{N(1)} - C_{2,g}^{N(1)}\left(\gamma_{qq}^{N(0)} - \gamma_{gg}^{N(0)}\right)\right]\right.$$

$$\left.-\left(\gamma_{qg}^{N(1)}\right)^2 + 2C_{2,g}^{N(1)}\gamma_{qg}^{N(1)}\left(\gamma_{qq}^{N(0)} - \gamma_{gg}^{N(0)}\right) - \left[C_{2,g}^{N(1)}\left(\gamma_{qq}^{N(0)} - \gamma_{gg}^{N(0)}\right)\right]^2\right\}$$

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Tests of NLO BFKL resummation

(C. Royon)

- LO BFKL very successful for F_2(proton), but with effective $\alpha_S \sim 0.1$ (should be ~ 0.2 for HERA kinematics)
- NLO BFKL - theoretical problems, expected NLO improvement fails
  - Solution: include resummation
- Test NLO BFKL including resummation using the same tests used for LO BFKL ("saddle point approximation")
- Tests not completely successful - need to identify reasons why

Factorisation & Event Generators

(X. Zu)

- Aiming to develop a nonleading order event generator for DIS - need to make the following requirements:
  - factorisation of differential cross sections
  - Exact parton kinematics
- In order to do this, use unintegrated parton correlation functions
  - Cannot integrate over final state
  - Replaces parton shower in LO MC generators
- Basic rules established, but need to extend them to cover QCD fully

Low-x physics from RHIC

- Rapidity dependence of high P_t suppression (BRAHMS/Videbaek)
- Nuclear modification factors for hadrons at forward & backward rapidities in deuteron-gold collisions at $\sqrt{s}$ = 200 GeV (PHENIX/Zhang)
- Neutral Pion suppression at forward rapidities in d+Au collisions at STAR (STAR/Rakness)
- Nuclear modification in d+Au collisions by colour glass condensate (Kovchegov)
- Forward production in d+Au collisions by parton recombinations (Fries)

Low x physics in nuclei

- Gluon density in a nucleus is enhanced by $A^{1/3}$ at a given impact parameter
- Nucleus is a better place to observe and study the phenomena of gluon recombination and gluon saturation

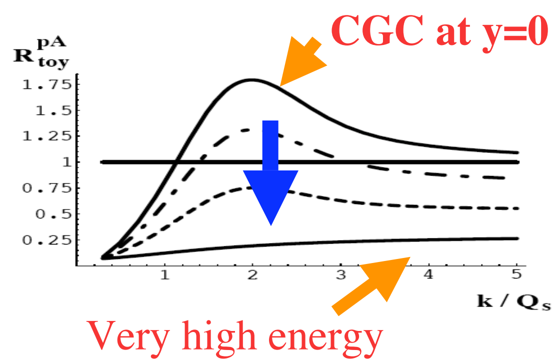
- Gluon recombination and coherent multiparton interactions
  - Suppression of gluon
  - Reduction of hadronic cross sections
- Gluon saturation
  - Colour Glass Condensate
  - (a new state of partons ?)
  - Effective field theory approach

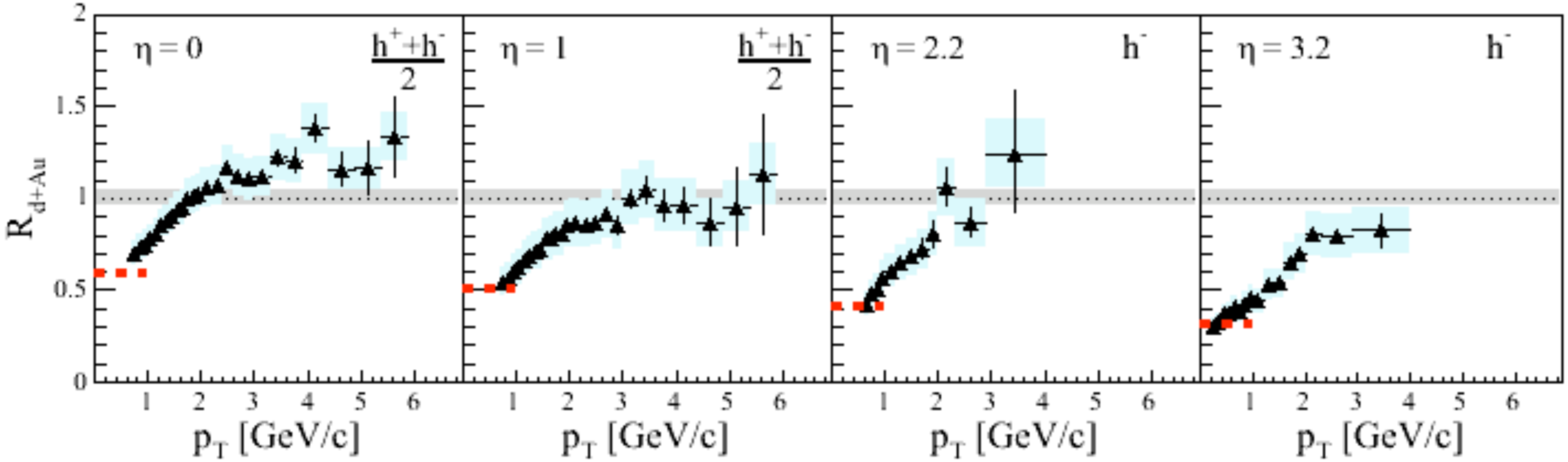
Rapidity dependence of high Pt suppression (BRAHMS)

(F. Videbaek)

- Determine from charged hadron multiplicity
- "Cronin effect" enhancement at $\eta \approx 0$
- Clear suppression up to $\eta = 3.2$

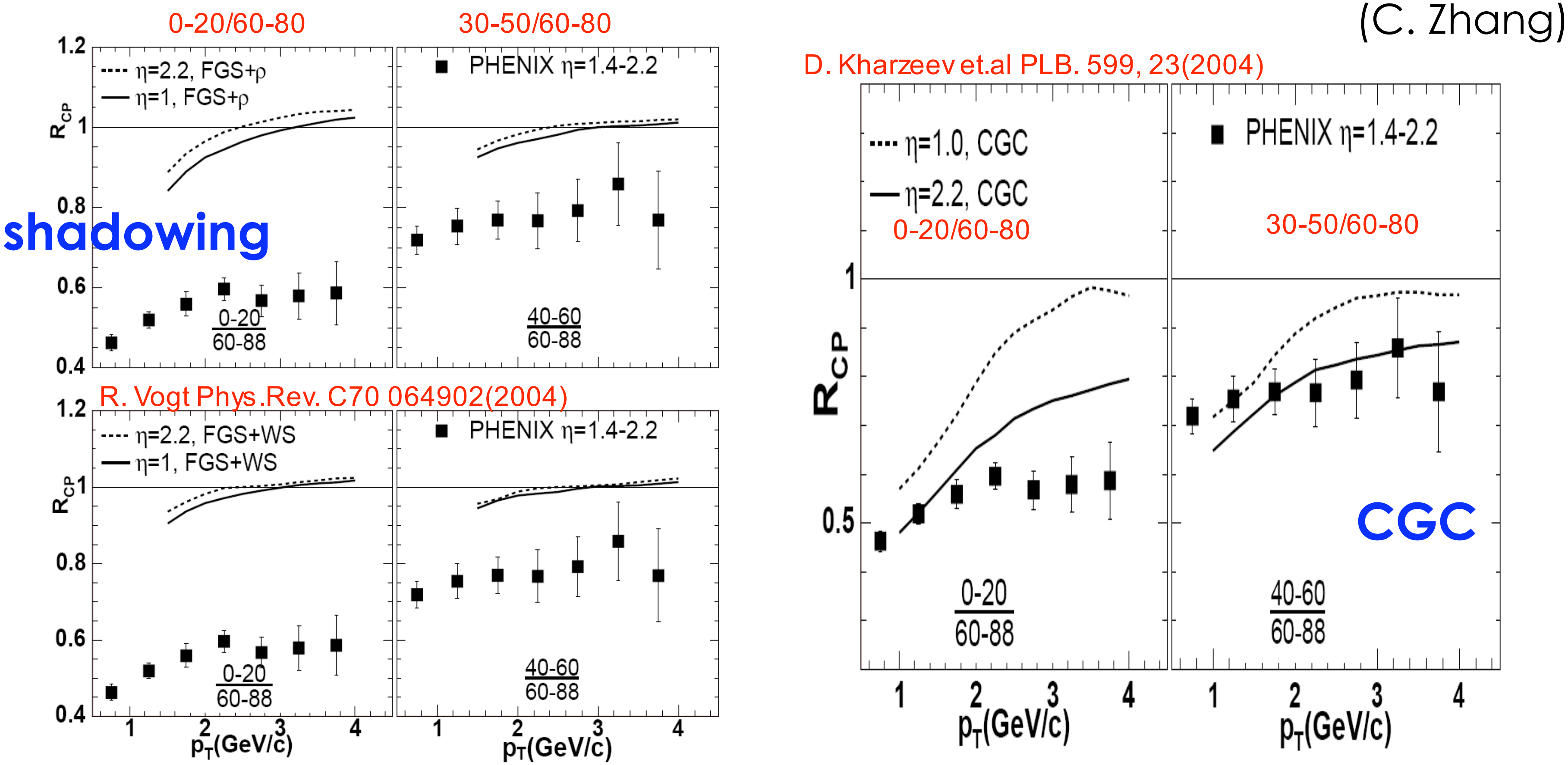
$$R_{dAu} = \frac{d^2N/dp_T d\eta(d+Au)}{N_{Coll} d^2N/dp_T d\eta(p+p)}$$





Measuring nuclear modification on hadron production (PHENIX)

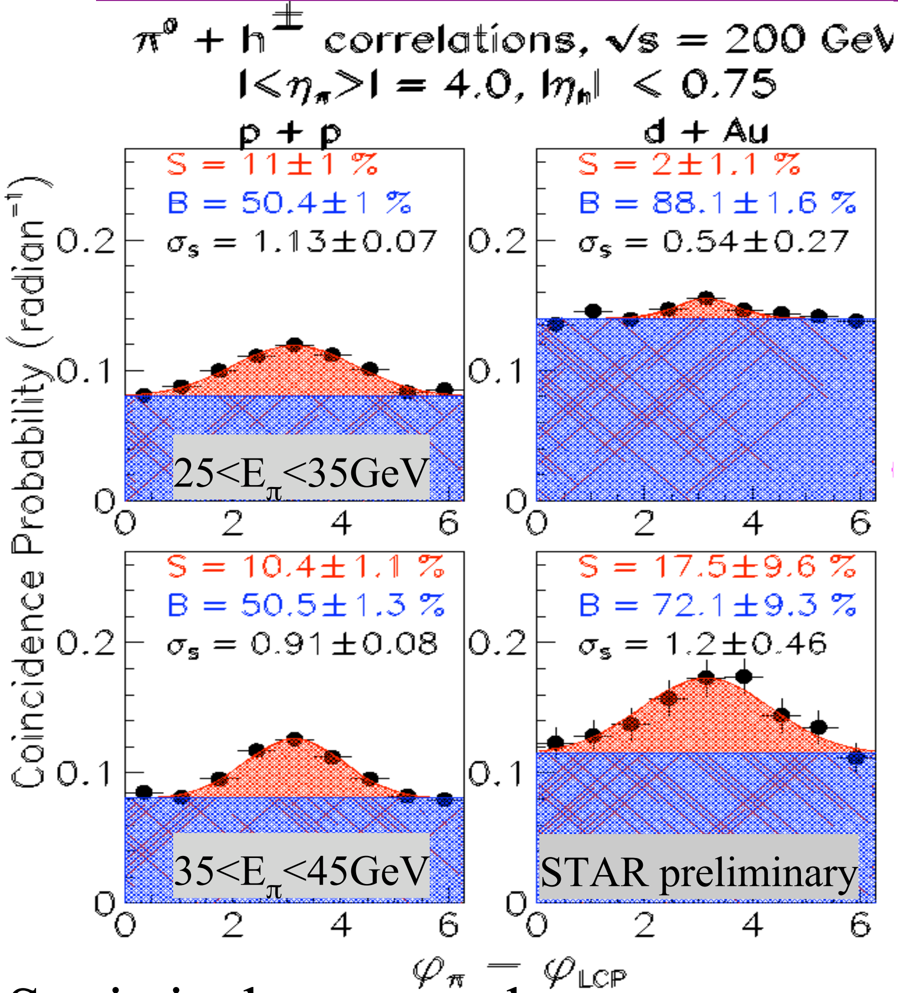
(C. Zhang)



R_{CP}: ratio of charged hadron multiplicity for central and peripheral collisions

Neutral pion suppression at forward rapidities (STAR)

(G. Rakness)



Statistical errors only

- Observe suppression compared to p-p
  - S = probability of correlated event
  - B = probability of uncorrelated event
- Consistent with shadowing/CGC predictions
- More data needed !

Nuclear modification in d+Au …

- … by colour glass condensate (Y. Kovchegov)
  - Model used by PHENIX for R_{CP}
  - Other predictions also made for azimuthal correlations
  - Evolution between jets makes correlations disappear in certain p_T region
    - Supported by measurements from STAR
- … by parton recombination (R. Fries)
  - Assume in dense parton systems that quarks recombine to form hadrons - important for intermediate p_T region
  - Recombination in d+Au explains $R_{dAu}(p) > R_{dAu}(\pi)$ at midrapidity (as observed by STAR)

Saturation

- Saturation, travelling waves & the BK equation at LL & NLL (Enberg)
- Nonlinear evolution equations in QCD (Stasto)
- Dense-Dilute Duality in high energy evolution (Kovner)
- Chaos in colour glass condensate (Tuchin)
- Gluon distributions & fits using dipole cross sections (Thorne)

- Summary of presentations from Jianwei …

BK equation and traveling waves

(R. Enberg)

- $\partial_Y \mathcal{N}(k,Y) = \bar{\alpha}\left[\chi(-\partial_L)\mathcal{N}(k,Y) - \mathcal{N}^2(k,Y)\right]$
  is a quite complicated integro-differential equation.
- Munier & Peschanski realized that it can be approximated by expanding the kernel:

$$\chi(\gamma) \simeq \chi(\gamma_c) + \chi'(\gamma_c)(\gamma - \gamma_c) + \frac{1}{2}\chi''(\gamma_c)(\gamma - \gamma_c)^2$$

  which brings the BK equation into the form of the Fisher–Kolmogorov–Petrovsky–Piscounov (FKPP) equation

$$\partial_t u = \partial_x^2 u + u - u^2$$

  ($t \sim Y$ and $x \sim L = \log k^2$)
- FKPP equation has *traveling wave* solutions

Chaos in the Color Glass Condensate

Discretization of BK equation

(Kharzeev, K.T., 05)

- Let's impose the boundary condition by putting a system in a box of size L~Λ^{-1}
- We can think of evolution as a *discrete process* of gluon emission when parameter $n=\alpha_s \ln(1/x)$ changes by unity.
- Evolution equation can be written as

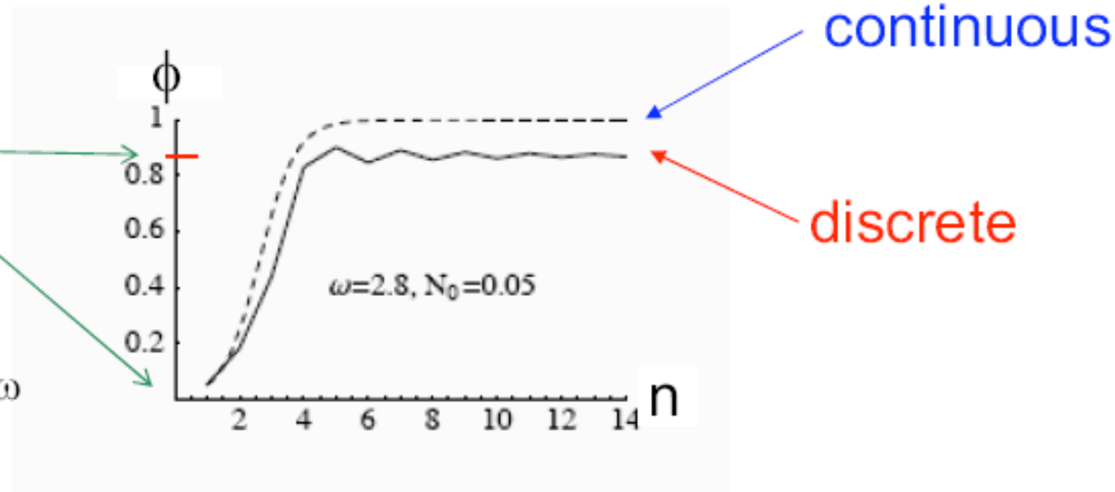
$$\varphi_{n+1}(k_\perp) = (\hat{\chi}+1)\varphi_n(k_\perp) - \varphi_n^{\,2}(k_\perp)$$

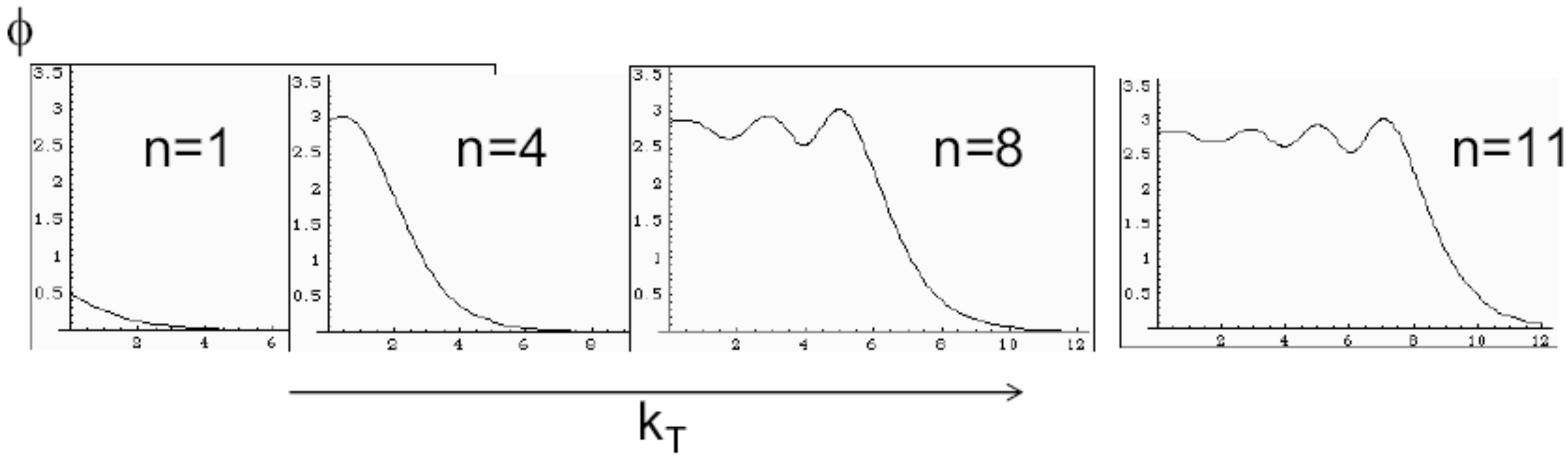
- Diffusion approximation: $\chi(\gamma) \approx 4\ln 2 + 14\zeta(3)(\gamma - 1/2)^2 + \ldots$
- Let's keep only the first term $\chi(\gamma) = \chi(1/2) \equiv \omega - 1.$

$1<\omega<3$

- Stable fixed point:
- Unstable fixed point:

$$\phi_{n+1} = \phi_n \Rightarrow \quad \phi_{n,fixed} = \begin{cases} (\omega - 1)/\omega \\ 0 \end{cases}$$

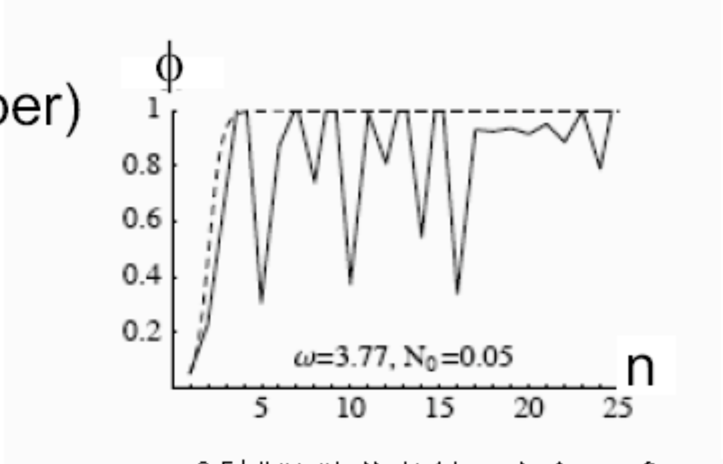


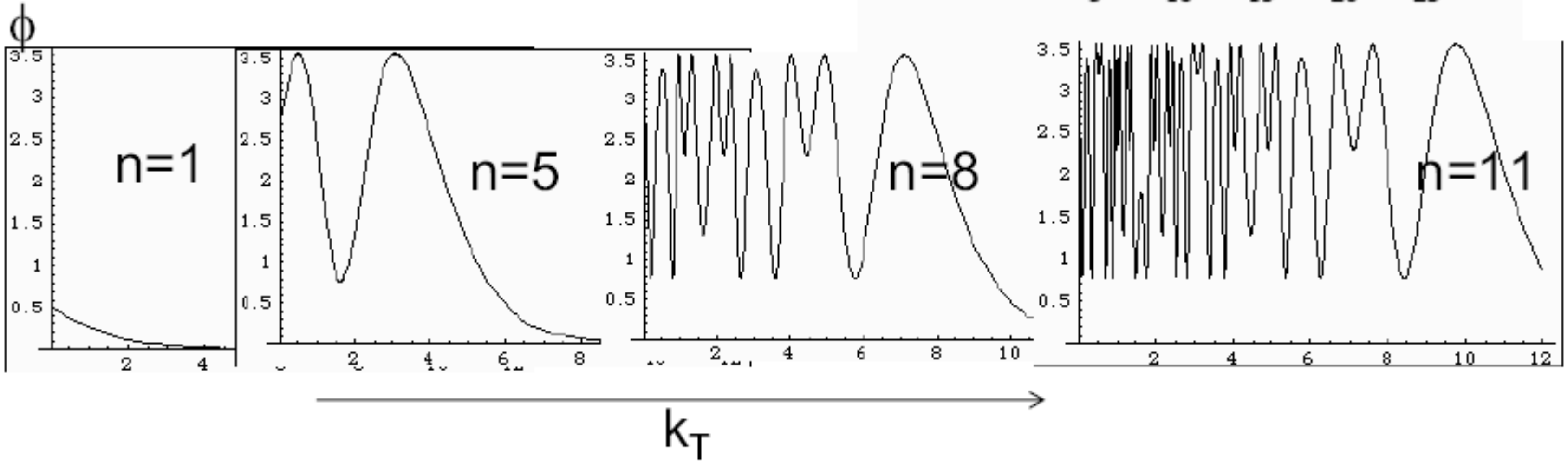


Onset of chaos

$\omega > \omega_F = 3.569$ (Feigenbaum's number)

- In pertubative QCD:
  $\omega > \omega_{min} = 1 + 4 \times \ln 2 = 3.77 > \omega_F$





Effective field theory approach

Effective action for scattering off color glass condensate
(Anna Stasto – BNL)

Quantum evolution of scattering amplitude for high energy collisions between a dilute and a dense system
(Alex Kovner – Univ. of Connecticut)

Duality between scattering amplitude between dilute-dense and dense-dilute collisions at high energy
(Alex Kovner – Univ. of Connecticut)

Parton distribution functions

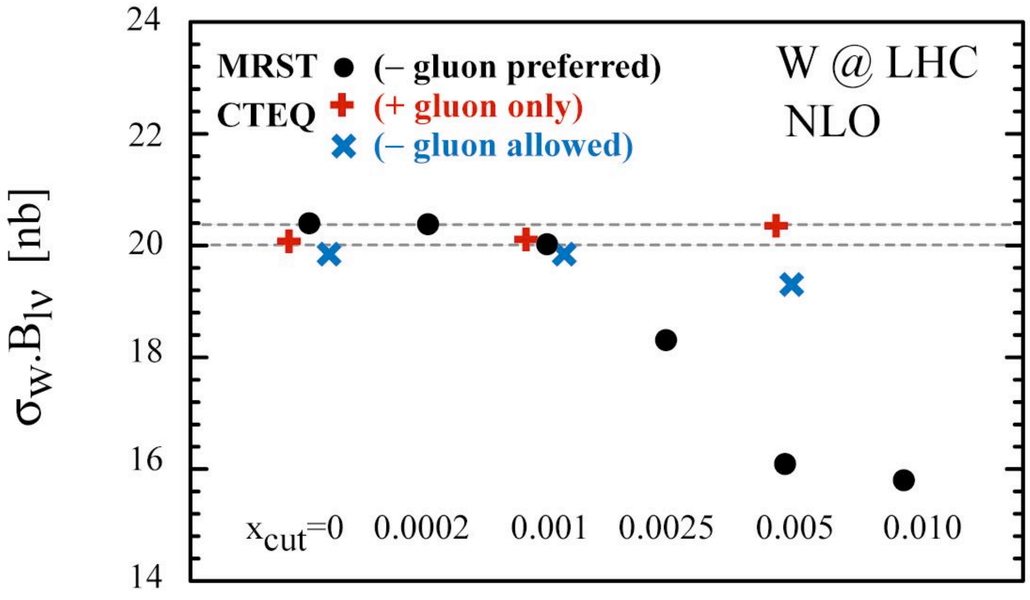
- Parton uncertainties & the stability of NLO global analysis (CTEQ/Stump)
- Recent progress in parton distributions & implications for LHC physics (MRST/Thorne)
- Proton PDFs using structure function & jet data from ZEUS (ZEUS/Terron)
- The Neural Network approach to PDF fitting (Rojo)

- Impact of future HERA data on the ZEUS PDF fit (Gwenlan-Barr)

Uncertainties & stability of PDFs

(D. Stump)

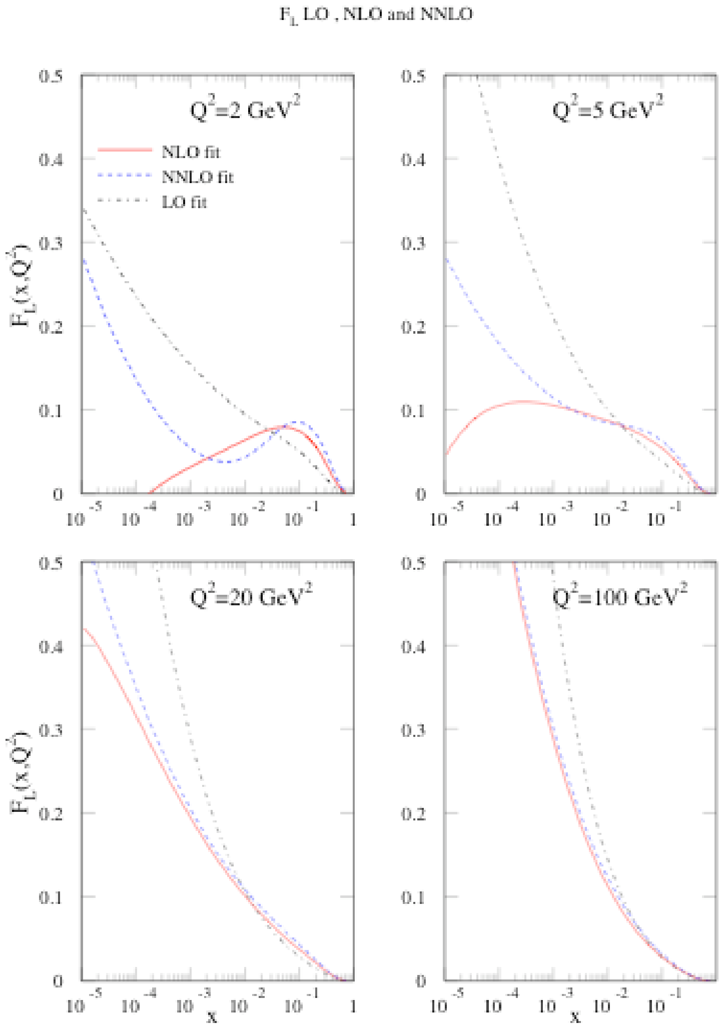
- Considered compatibility of datasets
- Are the final results of the global PDF fits stable ?
  - Considered recent analysis by MRST group
  - Studied stability with respect to x_{cut}, Q^2_{cut}



- CTEQ conclude that fits are stable
- MRST conclude: uncertainties increase significantly with tight x requirement; in any case NNLO is much more stable

Recent progress in PDFs - MRST

(R. Thorne)



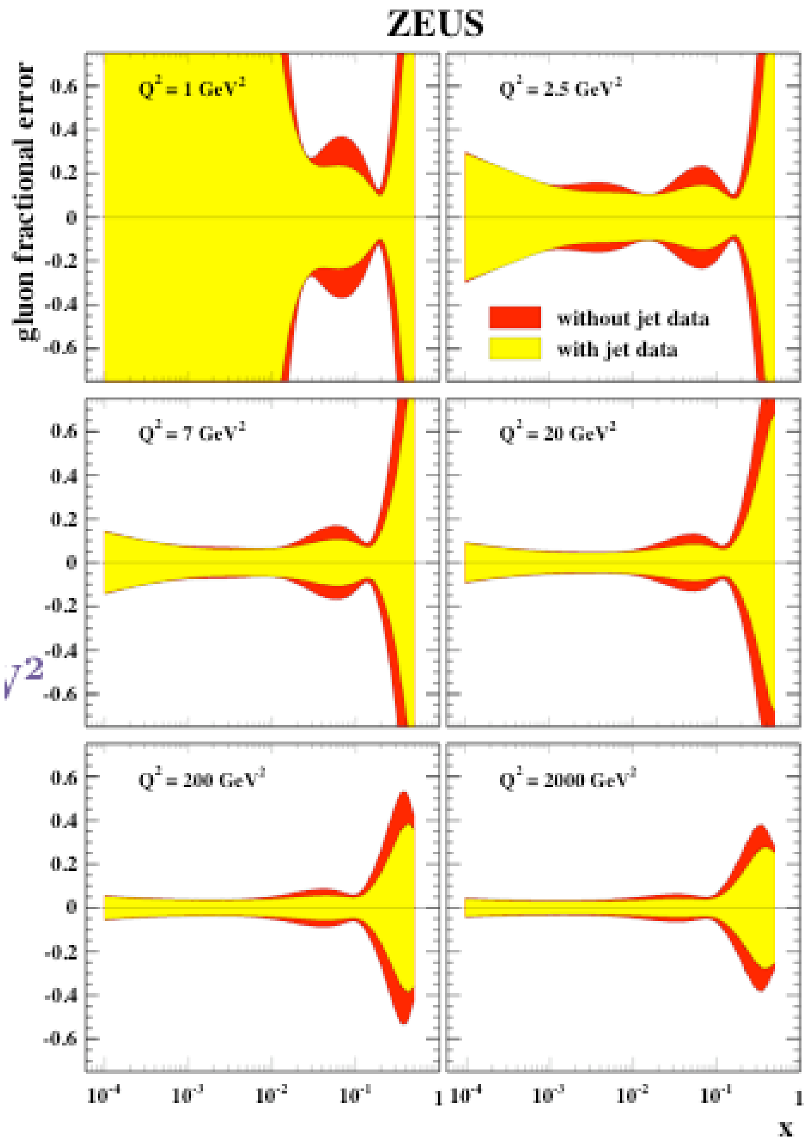
- Discussion of impact on LHC physics: W & Z cross sections; also jet cross sections
- General move towards NNLO PDFs - expect this to become the standard
  - But note the impact on certain distributions:

Recent progress in PDFs

- MRST also considered QED effects - would expect to be negligible, which they are …
- However, leads to small isospin violation
  - Results in improvement of prediction for prompt photon production at HERA

- Neural network approach to PDF fitting (NNPDF/J. Rojo)
  - Alternative approach - no bias from assumed functional form
  - Better estimation of PDF uncertainties
  - Structure functions determined; determination of PDFs underway

PDFs from ZEUS data



(J. Terron)

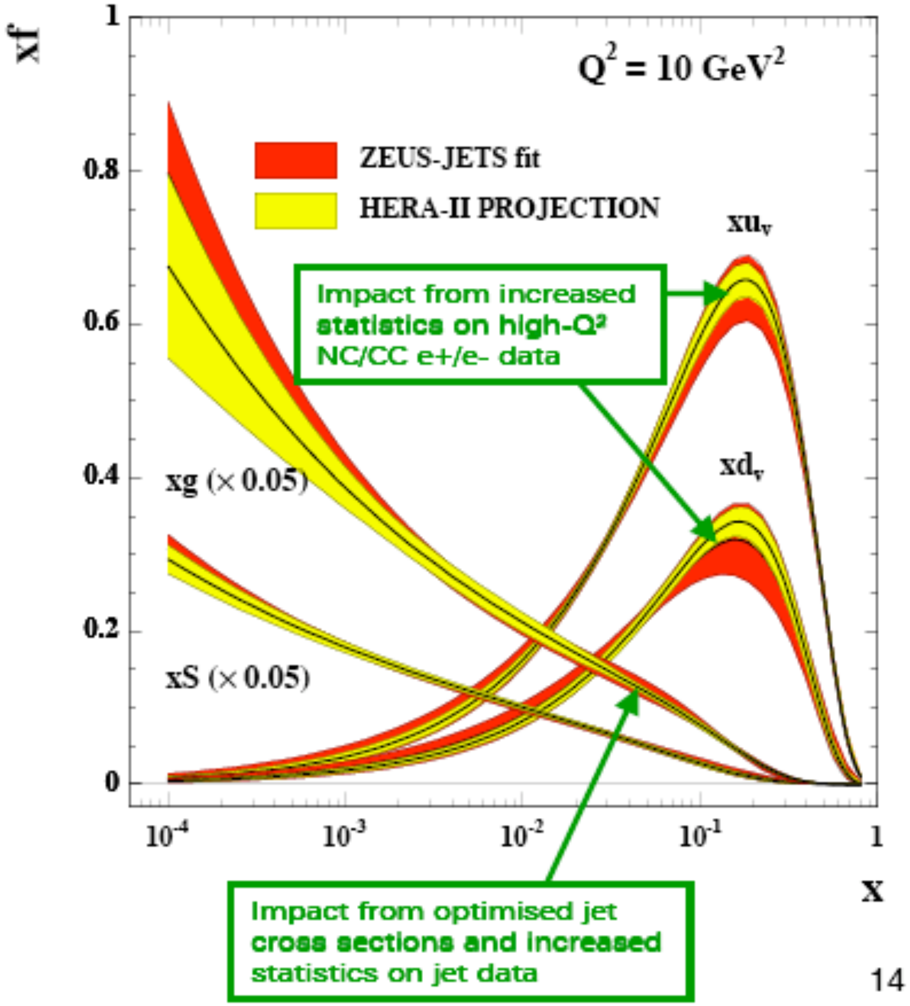
- Addition of NC DIS jet data and direct-enriched dijet photoproduction data to ZEUS PDF fit
- Improves gluon density uncertainties at moderate x
- Also allows precise α_S determination from ZEUS data alone:

  $\alpha_S = 0.1183 \pm 0.0058$
- Comparison to Bethke 2004:

  $\alpha_S = 0.1182 \pm 0.0027$

Impact of future HERA data on ZEUS PDFs

(C. Gwenlan-Barr)



- Consider impact of expected HERA-II running scenario on ZEUS PDFs
- Significant improvement in valence quark distributions
- Some improvements observed in gluon & sea distributions as well
- Also considered inclusion of precision HERA F_L results (low-x, low Q^2 gluon)
- e-D HERA running (sea quark asymmetries)

Low-x summary

- Lots of progress in low-x measurements & theory
- HERA-I structure function programme (almost) complete
- Searches for saturation effects at RHIC
- Developments in the theoretical description of saturation & the colour glass condensate
- Studies of data compatibility & PDF stability from PDF fitting collaborations
- First study of the impact of future HERA-II data on PDFs

And finally …

- Thank you to the organisers, speakers & session chairs for a very interesting and profitable meeting !